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## Solar Proton Spectrums in the Events of November 12 and 15, 1960

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**Abstract.** Freier and Webber have demonstrated that an exponential rigidity spectrum provides a good empirical fit to solar proton data over a wide range of rigidity and during widely different events. In this paper we discuss the conclusions they have drawn about the events of November 12 and 15, 1960, during which a series of rocket flights was made by the Goddard Space Flight Center. We find that for the November 12 event an exponential rigidity spectrum does not fit the observations, owing to the presence of a relatively large number of low-energy protons, and that data obtained late in the November 15 event are consistent with an exponential rigidity spectrum. We suggest that the difference in character of the spectrums observed in these two events is due to a flux of low-energy protons arriving at the earth on November 12 with the solar plasma responsible for concurrent geomagnetic disturbances. The flights made late in the November 15 event were during a geomagnetically quiet time.

AUTHOR

## INTRODUCTION

Freier and Webber [1963] have proposed an exponential rigidity form for the spectrums of solar particles. In deriving this form they used the results of balloon flights, neutron monitor and riometer observations covering an energy range from about 15 Mev to several bev.

The suggestion that high-energy particles from the sun have a rigidity spectrum of the form  $J = J_0 \exp(-P/P_0)$ , where  $J$  is the intensity above rigidity  $P$ ,  $J_0$  is the intensity above zero rigidity, and  $P_0$  is the characteristic rigidity, which is a function of time during a given event, has led us to re-examine (and rework) the results we obtained during the solar proton events of November 12 and 15, 1960. The purpose of this work is to test the fit of an exponential spectrum at low energies by means of direct particle observations.

In our original analysis [Ogilvie *et al.*, 1962; Davis and Ogilvie, 1962] we assumed the spectrum to be a power law in kinetic energy; hence we are interested in determining whether the exponential form provides a better fit to our data, and, if so, the extent to which the intensity values are changed.

## ANALYSIS

During the November 1960 solar proton events several rockets were fired from Fort Churchill by the Goddard Space Flight Center. These rockets carried both particle counters and

nuclear emulsions (characteristics of the particle counters are listed in Table 1).

We shall be concerned mainly with the observations obtained from the 0.25-g/cm<sup>2</sup> CsI scintillator. An integral pulse height analysis was performed on the pulses from this counter by altering the collector impedance of the phototube using a motor-driven switch followed by an amplifier with a fixed trigger level. This system has been fully described before, but it is necessary to re-emphasize that such a system introduces overlapping energy intervals with none of the limits common to all levels. An appropriate method of analysis is thus to assume a spectral form and then to compute the ratios of the rates in each interval as a function of one or two parameters and to compare the computed and observed ratios. The energy levels are illustrated in Figure 1. The solid curve shows energy loss as a function of energy for normally incident particles. All angles of incidence are taken into account in the analysis. Since we have four levels, three ratios are defined, and to get a meaningful result we can use only two

TABLE 1

Detector	Lower Energy Limit	Upper Energy Limit
Geiger counter	30 Mev	...
CsI Sc. counter	2 Mev	160 Mev
ZnS Sc. counter	0.2 Mev	4.5 Mev

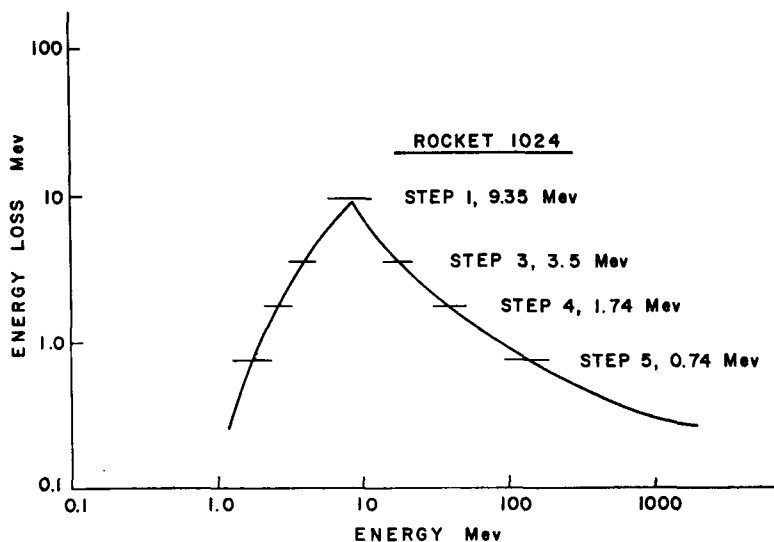


Fig. 1. Energy loss in 0.25-g/cm<sup>2</sup> CsI as a function of proton energy for normally incident particles. The integral energy loss discrimination levels for each step are shown by horizontal lines.

parameters. In our earlier paper we used  $n$ , the exponent in an integral power-law spectrum  $N = N_0 E^{-n}$ , and a low-energy cutoff  $E_c$ . The low-energy cutoff was introduced to account for the observation that the counting rates on the two lowest energy levels were often almost equal, showing that there were few particles in the energy region between their lower limits. We obtained in this way satisfactory fits for the three rocket shots into the November 12 event, and somewhat less satisfactory fits for the four rocket shots fired into the November 15 event. This paper discusses the results we have obtained by recalculating the ratios of the counting rates of the various energy levels assuming both a power-law spectrum and an exponential rigidity spectrum. For the exponential rigidity analysis we have used  $P_0$ , the characteristic rigidity parameter discussed by Freier and Webber, and  $W_p$ , the proportion of  $\alpha$  particles to protons in a given rigidity interval. For the power-law tests we have used separately two sets of two parameters: the exponent  $n$  and a low-energy cutoff  $E_c$ , and the exponent  $n$  and the proportion  $W_p$  of  $\alpha$  particles to protons in a given energy per nucleon interval.

#### RESULTS

Figure 2 illustrates several important features of the events of November 12 and 15. It shows

the Ottawa neutron monitor and meson monitor counting rates and the occurrence of solar flares and magnetic storm sudden commencements. Also shown are the times of firing of the NASA rockets and the values of the parameters which best fit the counter data, together with values of  $P_0$  deduced by Freier and Webber.

*November 12 event.* All the observations on November 12 took place during the active part of this complicated event. A class 3 flare at 1000 UT on November 10, which had no type IV emission and gave rise to no detectable particles, produced the sudden commencement at 1844 UT on November 12. By coincidence, this sudden commencement occurred during the arrival at the earth of solar protons emitted by the flare of 1320 UT on November 12.

The first rocket (NASA 1024) was fired at 1840 UT on November 12, four minutes before the sudden commencement. The second (NASA 1015) was fired approximately five hours later at 2332 UT, about 2½ hours after the second of two large increases in the earth's field. The third rocket (NASA 1016) was fired at 1603 UT on November 13 during the recovery from the 1500- $\gamma$  negative excursion that occurred at 1023 UT on November 13. The disturbed magnetic conditions at the time of these firings show that the magnetosphere was at these times immersed in a solar plasma stream.

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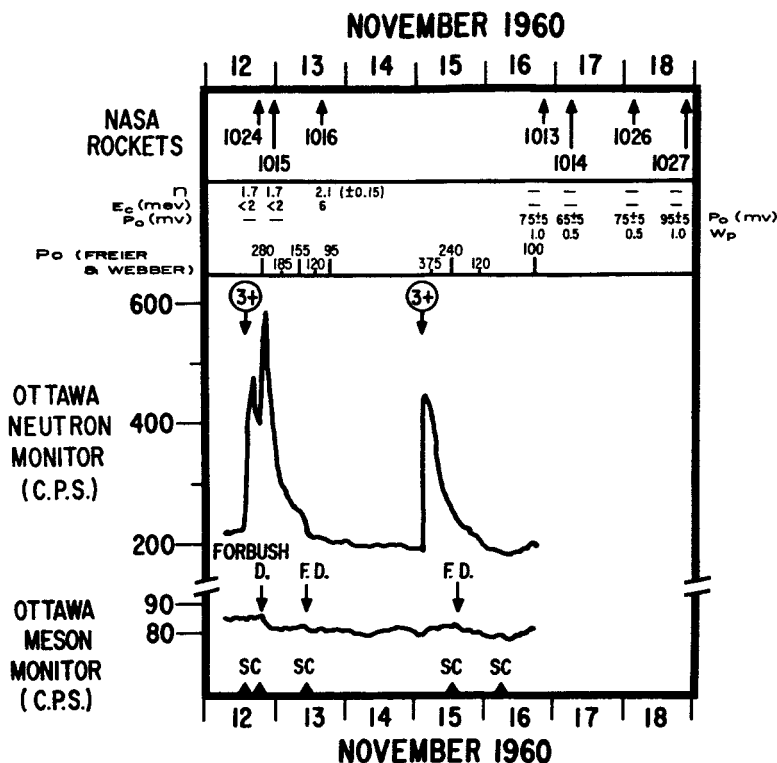


Fig. 2. The events of November 12 and 15, 1960, showing the times of NASA rocket flights, results obtained by Freier and Webber and the present work, and solar and terrestrial events.

Good fits to the data from the first two rockets were obtained using integral power-law spectrums with exponent  $n = 1.7 \pm 0.1$ . The analysis of the first of these flights (NASA 1024) is illustrated in Figure 3. We show the computed ratios of the rates on the three steps, 1, 3, and 4 to the rate on step 5 for two spectral forms. In diagram A the assumed spectrum is a power law in kinetic energy and in diagram B an exponential law in rigidity. The highest solid line in each diagram is the ratio of the rate on step 4 to the rate on step 5, the middle solid line is the ratio of the rate on step 3 to that on step 5, and the lowest line is the ratio of the rate on step 1 to that on step 5. In general the observed ratios, which are shown as horizontal lines (with errors), cut the corresponding computed curve twice. In diagram A an intersection of the observed ratios with the corresponding computed curves occurs for  $n = 1.7 \pm 0.1$ , indicating a fit to a power law with this integral exponent. In diagram B a single value of characteristic rigidity consistent with the observed and computed

ratios cannot be found. There is a set of intersections between 20 Mv and 40 Mv; we reject this poor fit, since it is inconsistent with other measurements. The results from the third rocket can be fitted with a power-law spectrum of exponent  $n = 2.1 \pm 0.15$  and  $E_c = 6.0$  Mev, and somewhat less satisfactorily by an exponential rigidity spectrum with  $P_0 = 65$  Mv. These results are essentially the same as those given in our first paper [Ogilvie *et al.*, 1962].

We have re-examined the evidence for the low-energy protons (from 0.2 to 4.5 Mev) detected by the ZnS scintillation counter and find that the spectrum given in Figure 9 of our earlier paper [Ogilvie *et al.*, 1962] remains unchanged.

*The November 15 event.* The times of rocket firings into this event are shown in Figure 2. During the November 15 event all firings were made during magnetically quiet times, between 41 and 91 hours after the flare. An exponential rigidity spectrum provides a good fit to the data from these flights. The analysis of the first of these flights (1951 UT, November 16) is pre-

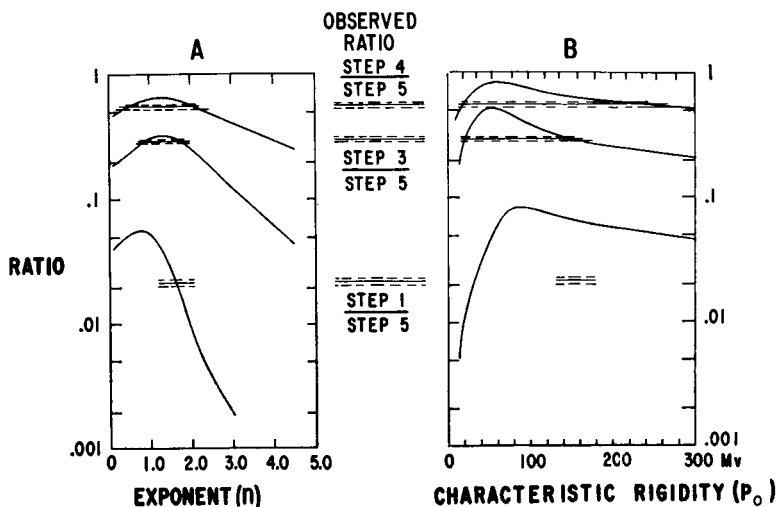


Fig. 3. The analysis of the first rocket flight (NASA 1024, 1840 UT, November 12, 1960). The horizontal lines represent the observed ratios, with errors, and curves show computed values of the ratios as a function of exponent  $n$  (diagram A) and characteristic rigidity  $P_0$  (diagram B).

sented in Figure 4 as an example. The arrangement of Figure 4 is similar to that of Figure 3. The fit to the exponential rigidity spectrum is shown in diagram C. We find that, in order to make the fit, it is necessary to postulate a value of  $W_p$  close to unity. This high proportion of  $\alpha$  particles is in agreement with measurements made at higher energies earlier in the same event [Freier, 1963]. Diagram A shows that a power-law spectrum with a low-energy cutoff does not fit the data even when the cutoff energy  $E_c$  is as high as 6 Mev. Diagram B of Figure 4 shows

that a power-law spectrum with a value of  $W_p$  of 0.07 provides a fit as close as that provided by the exponential rigidity spectrum. This value of  $W_p$  is consistent with measurements made on the same rocket by Biswas and Fichtel (private communication).

In the three later flights into the November 15 event the fit given by the exponential rigidity spectrum is decisively better than that given by the power law for any proportion of  $\alpha$  particles. As can be seen from the data given in Figure 2, direct comparison of the value of  $P_0$  obtained

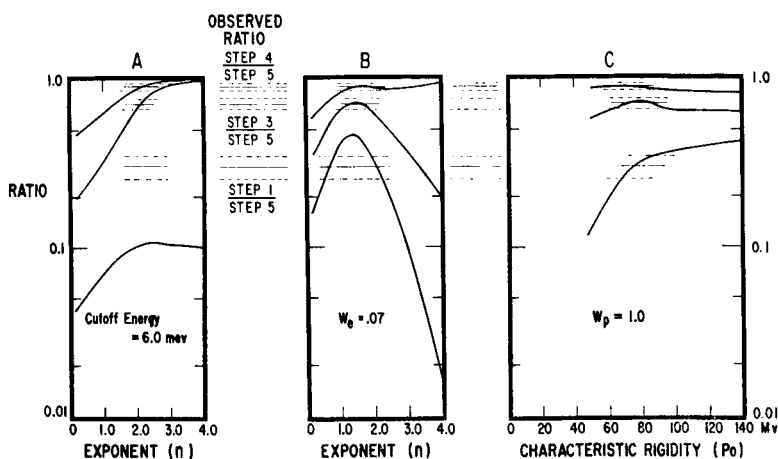


Fig. 4. The analysis of the first rocket flight into the November 15 event (NASA 1013, 1951 UT, November 16, 1960). For explanation see text.

TABLE 2. Comparison of Intensity Values in the November 15 Event Obtained by Two Different Analyses

Rocket	Time	Intensity: p/cm <sup>2</sup> sec ster > 10 Mev	
		Power-Law Analysis	Rigidity Analysis
NASA 1013	1951, Nov. 16	530 ± 50	430 ± 70
NASA 1014	0600, Nov. 17	200 ± 40	460 ± 100
NASA 1026	0339, Nov. 18	150 ± 20	140 ± 30
NASA 1027	2139, Nov. 18	45 ± 5	25 ± 5

from this experiment with the value of  $P_0$  obtained by Freier and Webber can be made only in one case. Although the disparity in this case is outside that expected from statistical fluctuations, we note that the values of  $P_0$  we observed on November 17 and 18 are in agreement with the values to be expected from the lowering of  $P_0$  with time on November 15 and 16 as observed by Freier and Webber.

We now compare in Table 2 the intensity above 10 Mev deduced by means of the exponential rigidity spectrum with that previously obtained by means of a power law in kinetic energy. This comparison is made at 10 Mev, since particles of this energy can produce counts on all steps (taking into account particles whose trajectories are inclined to the axis of the crystal).

Table 2 shows that the rigidity analysis which gives the better fit to the data yields intensity values within a factor of 2 of those given by the power-law analysis. As Figure 5 shows, the rigidity analysis provides a good fit to data obtained at other energies.

In interpreting the counting rates of the ZnS counter in the November 15 event, we now think it possible that a large proportion of these counts could have been caused by higher-energy particles passing through the cathode of the phototube, and this therefore throws some doubt on the rising parts of the spectrums below 1 Mev indicated in an earlier paper [Davis and Ogilvie, 1962]. It should be mentioned here that this is not the case for the November 12 event, for which direct evidence from the absorption curves leaving and entering the atmosphere confirms the existence of low-energy particles.

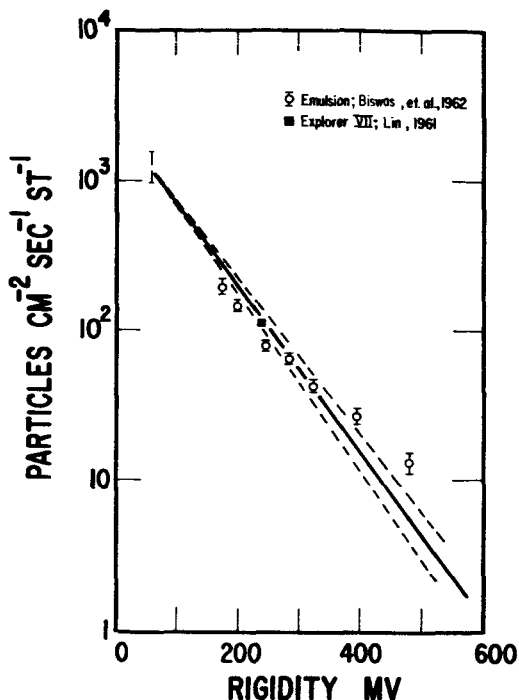


Fig. 5. A comparison of the emulsion and counter results for the spectrum on flight NASA 1013, and an intensity derived from counter measurements on Explorer 7.

#### CONCLUSIONS

1. Neither the exponential rigidity spectrum nor any other functional form we have tried will at all times represent the low-rigidity end of the solar proton spectrum.

The fact that the exponential rigidity form does not always fit does not conflict with any of the observations used by Freier and Webber since the detectors from which they obtain low-energy particle information were riometers for which the differential sensitivity to protons falls rapidly with decreasing energy below about 15 Mev (D. E. Guss, private communication). A consequence of this result is that an extrapolation of the spectrum measured above 15 Mev down to zero rigidity provides a value of  $J_0$  which, although it is a useful parameter to describe the high-energy spectrum, is not necessarily the same as the intensity above zero rigidity.

2. We suggest that the low-energy protons observed on November 12 were associated with the arrival at the earth of the solar plasma re-

sponsible for the very disturbed geomagnetic conditions at that time.

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